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Analysis of identified particle yields and Bose-Einstein (HBT) correlations in p+p collisions at RHIC

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Abstract. Simultaneous Buda-Lund hydro model fits are presented to identified particle spectra and two-particle Bose-Einstein correlations as measured by the STAR collaboration in $\sqrt{s} = 200$ GeV p+p collisions at RHIC. Preliminary results are compared to similar results in Au+Au collisions at RHIC, hadron+p reactions as well as Pb+Pb collisions at CERN SPS.

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1. Introduction

The Buda-Lund hydrodynamic model [1, 2] was shown to describe in a statistically acceptable manner the single particle spectra and the two-particle Bose-Einstein correlations in hadron+proton collisions at CERN SPS [3]. The model, with different source parameters, also described well the identified single particle spectra and the two-particle Bose-Einstein correlations in Pb+Pb collisions at CERN SPS [4]. Similarly, the Buda-Lund hydro model described well the single particle spectra and the two-particle Bose-Einstein correlation functions in Au+Au collisions at RHIC [5], both at $\sqrt{s_{NN}} = 130$ and 200 GeV colliding energies. The model was recently reviewed in ref. [6] and it was extended to describe elliptic flow in non-central heavy ion collisions at RHIC energies in refs. [7, 8].

We have observed in these works, that the RHIC Au+Au data are well described by the model with a relatively high central temperature of 214 ± 7 MeV in 0-10 % central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV and 200 ± 9 MeV central temperature in the less central, 0-30 % Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

The same analysis suggests, that the surface (or with other words, the average) temperature of the hadronic final state is remarkably low, around $T_0/2$, nearly 100 MeV in these reactions.

Lattice QCD calculations estimated the critical temperature of the hadron - quark gluon plasma phase transition near $\mu_B = 0$ to be $T_c = 172 \pm 3$ MeV [9], which was recently calculated more precisely, using the physical quark masses, to be $T_c = 162 \pm 2$ MeV [10], even lower than thought before. Thus the Buda-Lund data analysis of central Au+Au spectra and correlation radii implies the existence of a superheated hadron gas in the very middle of the Au+Au collisions at RHIC, providing an indirect indication for the transition to deconfined matter [5]. However, at the lower CERN SPS energy, the central temperature was found, in similar frameworks, to be within errors the smaller 139 ± 6 MeV, both in hadron+proton collisions [3] and in Pb+Pb collisions [5], in line with the arguments of Landau that the freeze-out temperature of a hadron gas should be approximately the π^0 mass, the mass of the lightest neutral quanta that can be excited in such a system.

In this work we investigate two questions:

a) Can a hydrodynamical model describe successfully the final state (identified particle spectra and Bose-Einstein correlations) in p+p collisions at RHIC?

b) What are the best hydro model parameters and how they correspond to the values for hadron+p reactions at CERN SPS and Au+Au collisions at RHIC ?

To answer these questions, we utilize as a tool the Buda-Lund hydrodynamical model. This model has been successfully applied to describe the double-differential invariant momentum distribution of charged particles in hadron+proton [3] and Pb+Pb collisions [4] at CERN SPS fixed target experiments, as well in Au+Au collisions at the RHIC collider energies of $\sqrt{s_{NN}} = 130$ GeV and 200 GeV [5]. Very few, if any, other models pass all of these tests (as far as we know).

2. The Buda-Lund hydro model

The Buda-Lund hydro model was formulated in refs. [1, 2], based on the following four principles:

– The particle emitting source consist of two, physically very different regions, the core and the halo. The core is a fireball like a star, the halo consists of the decay products of long-lived resonances, with relatively large length-scales, reminiscent to the solar wind surrounding the star. The large length-scales in the halo are assumed to be larger than the maximal length-scale resolvable by particle interferometry.

– The core is described by a locally thermalized, three dimensionally expanding particle emitting source. For central collisions, we utilize axial symmetry, for semi-central collisions, ellipsoidal symmetry to constrain the structure of the flow velocity, the fugacity and the local temperature distributions.

– We parameterize the hadronic final state in such a way, that it corresponds to know solutions of (relativistic or non-relativistic) hydrodynamical solutions in certain domains of the parameter space. In these limiting cases, even the time

evolution of the local densities and the velocity field can be followed.

– We constrain the parameterization in such a way, that the observables can be calculated analytically from the model. This is useful, as simple scaling laws are observed experimentally in the transverse momentum spectra as well as in the Bose-Einstein (HBT) correlation functions. The Buda-Lund hydro model observes these scaling behaviors in certain domains of the parameter space.

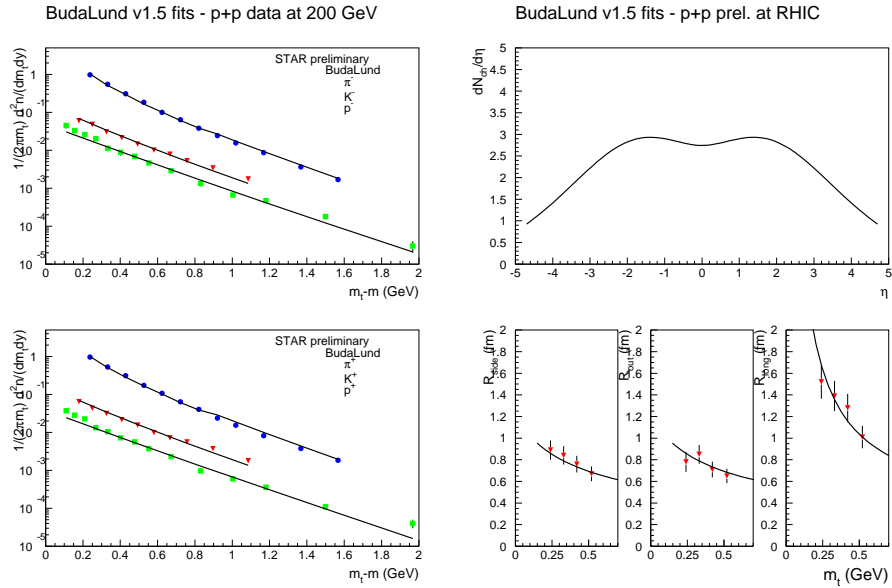## 2.1. Hydro in soft hadron+hadron collisions

Fig. 1. The Buda-Lund hydro model is fitted here simultaneously to STAR single particle spectra[11, 12] and STAR preliminary two-pion correlation radius parameters [13] in p+p collisions at $\sqrt{s} = 200$ GeV, with small amount of transverse flow, but with a large central temperature $T_0 \geq T_c$. The best fit parameters are summarized in Table I. The upper plot on the right side indicates the predicted pseudo-rapidity distribution of charged particles these collisions: BRAHMS and PHOBOS data can be used later, to restrict the source parameter $\Delta\eta$.

Recently, the STAR collaboration reported the identified particle spectra and the two-particle Bose-Einstein correlation radii in proton+proton collisions at the maximal RHIC colliding energy of $\sqrt{s_{NN}} = 200$ GeV. At the Quark Matter 2004 conference, the transverse mass dependence of these radius parameters was pre-

sented as one of the new HBT puzzles at RHIC [15]. However, the transverse mass dependence of the HBT radii in p+p collisions at RHIC is very similar to the transverse mass dependence of these radii in hadron+proton reactions at the lower CERN SPS energies [16], which were well described in terms of the Buda-Lund hydrodynamical model, together with the rapidity and transverse mass dependent double differential spectra of charged particles [3]. In that case, the transverse mass dependence of these HBT radii was not generated by the transverse flow, but by the transverse temperature inhomogeneities of hadron+proton collisions.

Perhaps it is surprising, that hydrodynamical descriptions work in the soft domain of high energy hadron+hadron collisions. However, Fermi and Landau initiated the statistical and hydrodynamical description of particle production for nucleon-nucleon as well as for nucleus-nucleus collisions. After accepting the hydrodynamical language, it is not surprising that the transverse temperature gradients play major role in hadron+hadron collisions - these systems have a rather small, typically 1 fm transverse radius, and the hot hadronic matter inside is surrounded with a vacuum that has zero temperature, so the temperature decreases on a small transverse radial scales, as compared to high energy heavy ion reactions, where the temperature decreases on a factor of 5-10 times larger scales.

2.2. Buda-Lund fit results

In this section we show fit results to STAR final identified particle spectra [11, 12] and two-pion Bose-Einstein correlation radii [13] in p+p collisions at $\sqrt{s} = 200$ GeV. First we investigate the question, is it possible to fit these data with the same central freeze-out temperature and transverse flow parameter, as were obtained [3] in hadron+p collisions at CERN SPS?

The answer is no, as also show graphically in the presentation version of this work [14], however, this bad fit cannot be shown here due to space limitations. But the conclusion is clear: When fixing the freeze-out temperature in the center of the fireball to $T_0 = 140$ MeV and the transverse flow to $\langle u_t \rangle = 0.2$, as in ref. [3], it is not possible to tune the other parameters of the Buda-Lund hydro model to describe the STAR p+p data at RHIC.

However, the Buda-Lund hydro model can successfully describe all these observables in p+p collisions, when the central temperature and the transverse flow parameters are released, as shown in Fig. 1. From this comparison one learns, that the central temperature in p+p collisions at RHIC is significantly larger, than in h+p collisions at CERN SPS, although the transverse flow parameter is in both cases within errors compatible with zero. The fit parameters are summarized in Table 1.

3. Conclusions

Let us quote Landau, who wrote [17] in 1956: "Experiment shows that in collisions of very fast particles a large number of new particles are formed in multi-prong

parameter	p+p 200 GeV		Au+Au 200 GeV		Au+Au 130 GeV	
T_0 [MeV]	289	$\pm$ 8	200	$\pm$ 9	214	$\pm$ 7
T_e [MeV]	90	$\pm$ 42	127	$\pm$ 13	102	$\pm$ 11
μ_B [MeV]	8	$\pm$ 76	61	$\pm$ 40	77	$\pm$ 38
R_G [fm]	1.2	$\pm$ 0.3	13.2	$\pm$ 1.3	28.0	$\pm$ 5.5
R_s [fm]	1.1	$\pm$ 0.2	11.6	$\pm$ 1.0	8.6	$\pm$ 0.4
$\langle u'_t \rangle$	0.04	$\pm$ 0.26	1.5	$\pm$ 0.1	1.0	$\pm$ 0.1
τ_0 [fm/c]	1.1	$\pm$ 0.1	5.7	$\pm$ 0.2	6.0	$\pm$ 0.2
$\Delta\tau$ [fm/c]	0.1	$\pm$ 0.5	1.9	$\pm$ 0.5	0.3	$\pm$ 1.2
$\Delta\eta$	3.0	fixed	3.1	$\pm$ 0.1	2.4	$\pm$ 0.1
χ^2/NDF	89.7	/ 69	132	/ 208	158.2	/ 180

Table 1. Buda-Lund hydro model v1.5 source parameters, corresponding to Fig. 1. The errors and the fit parameters are preliminary, as some of the fitted points are not yet final and the statistical and systematic errors were added in quadrature in these fits.

stars. The energy of the particles which produce such stars is of the order of 10^{12} eV or more. A characteristic feature is that such collisions occur not only between a nucleon and a nucleus, but also between two nucleons."

The Buda-Lund hydro model describes in a statistically acceptable manner the soft identified particle spectra and two-particle Bose-Einstein correlation data of STAR in p+p collisions at $\sqrt{s} = 200$ GeV. The temperature distribution has a maximum which is significantly above the critical $T_c = 162 \pm 2$ MeV value [10], but falls rapidly, within about 1.2 fm transverse distance, towards the vanishing temperature of the vacuum.

Our results are in contrast to the recent statement by Shuryak [18], who claimed that a hydrodynamical approach cannot describe the data in p+p collisions at the RHIC energy domain. It seems to us that Landau's insight was more precise in this particular case. Even more surprising, the flow velocity profile, within the errors of reconstruction, corresponds to the Hwa-Bjorken famous 1+1 dimensional relativistic hydrodynamical solution [19, 20]. In the transversally more extended Au+Au collisions we find evidence for a fully developed, three dimensional Hubble flow [5]. For similar results, see [21, 22, 23, 24, 25].

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